MEDITERRANEAN SOILS

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Contents

Summary

Mediterranean soils are soils which form under a Mediterranean climate. They are variously called *Terra Rossa* (on hard limestone) and Red Mediterranean Soils. Not all soils in a Mediterranean environment are, however, qualified as such because normal pedogenetic development may be hampered by erosion (rejuvenation of the profile), lack of time, lack of water or unfavorable parent material characteristics.

The role of climate, topography, parent material (mineralogical composition, coherence and permeability), time and human influence as soil forming factors is discussed. Pedogenesis is reviewed and three phases in a color sequence are recognized, with a major focus on soils developed over carbonaceous substrata. It is shown that the red phase corresponds to a climax development, but that as soon as environmental conditions are not optimal, this phase is not reached. The position of Mediterranean soils in the three major world classification systems is commented.

In terms of land use and production potential these soils are intensively used for both rain-fed and irrigated cropping. Under rain-fed conditions the choice of crops is limited to those that support a limited period of water supply in the year. Horticulture, citrus production and floriculture provide excellent cash returns, particularly because they can often be marketed as off-season crops.

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1. Introduction

Mediterranean soils are soils which, by definition, form under Mediterranean climatic conditions. The main characteristic of the Mediterranean climate is that it has two well defined seasons in the year, with the rain period coinciding with low temperatures (winter) while summers are hot and almost completely dry.

In the world as a whole, Mediterranean soils are not very extensive. FAO (1991) estimates their extension at approximately 420 million ha. The main area is around the Mediterranean Sea, with smaller areas in California, Chile, The Western Cape Province of South Africa, and West and South Australia (Figure 1).

Figure 1. Extension of Mediterranean soils (adapted from FAO, 1991).

2. Soil Forming Factors

2.1. Climate

The main characteristic of the Mediterranean climate is the alternation of a moist cool winter and a hot dry summer exceeding generally 3 to 4 months. Expressed in terms of soil temperature and soil moisture regimes, *sensu* Soil Taxonomy (USDA, 1975) and updates (Soil Survey Staff, 2003), Mediterranean soils have:

- a *xeric* moisture regime, whereby most of the rainfall occurs immediately after the winter solstice, and is followed by a relatively important dry period after the summer solstice;
- a temperature regime which is *thermic* (mean annual soil temperature between 15° and 22°C) or occasionally *mesic* (8°-15°C), e.g. intermediate between temperate regions and the tropics.

Soil formation and weathering in Mediterranean soils is most active during the rainy winter when also evapotranspiration is minimal. The conditions are then optimal for an effective dissolution and leaching of calcium carbonate and other easily soluble elements, as well as for the migration of clay. During the hot, dry summer the soil desiccates, causing the development of red dehydrated oxidized iron compounds (hematite, magnetite, etc.) within the profile.

Chemical soil processes related to available soil water refer in the first place to the decomposition, dissolution and leaching of easily soluble components. In soils developed over calcareous substrata this leads to a progressive decrease of the $CaCO_3$ content and ultimately to its more or less complete elimination from the profile. This goes together with a decrease of soil pH from 8.0-8.2 to approximately 7.0-7.2 and a tendency towards a de-saturation of the cation exchange complex. On non-carbonaceous and acid substrata, like granites, gneiss or sandstones, natural leaching and plant acid exudation intensify the processes of acidification (soil pH between 6.0 and 7.0) and de-saturation during the winter period. Moreover, in a free draining soil environment clay particles in suspension in the percolating soil water migrate into the deeper layers of the profile. The relative importance of clay migration varies with the amount of rainwater that penetrates the soil, inherent soil permeability, clay dispersion, parent material and time.

During the dry summer period the pedoclimate is completely different, and dissolution, leaching and clay migration are temporarily stopped or even reversed, while the soil solution gets re-saturated. Hence, pH variations between summer and winter may in one and the same horizon be as high as one unit, especially in soil sections with high organic matter content. In addition, iron compounds become oxidized and a red matrix color develops.

The result is the development of what is commonly referred to as a Red Mediterranean Soil or *Terra Rossa* (on carbonaceous rocks), though not all soils under this climatic regime reach this stage. The myth of Red Mediterranean Soil being dominant in this climatic area is therefore not substantiated in soil surveys, and the region is obviously more diverse in soils than any other climatic region, as shown by De la Rosa (1984) and Yaalon (1997). In this respect it should also be reminded that the connotation of *Terra Rossa*, as introduced by Reifenberg (1947) and Kubiena (1953) referred initially only to Mediterranean soils over hard limestone. In modern literature it has often been (erroneously) extended to all Red Mediterranean soils, including those over other types of rocks.

2.2. Parent Material

Parent material influences the formation of Mediterranean soils through its mineralogical composition, coherence, and permeability for water. Mineralogy influences the amount, particle size distribution and type of weathering products wherein the soil profile develops; coherence or hardness determines the resistance to weathering and speed of disintegration; permeability influences the intensity of physicochemical transformations within the original rock residue.

The variety of parent rocks in Mediterranean areas is quite large, though carbonaceous rocks seem to be the most extensive parent material. Around the Mediterranean Sea calcareous sedimentary rocks (limestone, dolomite, marl) with different behaviors in terms of mineralogical composition, hardness and permeability dominate. In South Africa and Australia, non-calcareous sedimentary rocks ranging from sandstone to mudstone and shale are well represented. Elsewhere, plutonic (granite), volcanic (basalt) and metamorphic rocks (quartzite, gneiss) are observed.

Mineralogy - Rocks have various compositions, and each of these components behave differently in terms of *solubility* when subject to weathering and disintegration. The mineralogical evolution on carbonaceous rocks in general starts with a chemical attack and dissolution of calcium carbonate by percolating rain water, especially when enriched by CO_2 and plant exudates:

$$CO_2 + H_2O \Leftrightarrow H_2CO_3$$
$$\downarrow$$
$$CaCO_3 + H_2CO_3 \Leftrightarrow Ca(HCO_3)_2$$

whereby the less soluble $CaCO_3$ in the substratum first reacts with H_2CO_3 and is then transformed into easily soluble $Ca(HCO_3)_2$ and then evacuated by the drainage water. Whether the dissolution of the rock is complete or not, leaving behind a weathering product with a variable amount of free $CaCO_3$ depends on the nature and hardness of the substratum and on the amount and chemical aggressiveness of the water that percolates through the soil and rock.

Weathering of silicates or volcanic glass releases silica into solution, which can migrate and/or precipitate as opal, nodules or crusts (duripans). Mature soils developed on these materials have acid surface horizons, with pH and base saturation generally increasing with depth.

The mineralogical composition of the parent material determines also the *texture* of the weathering product. Granites containing large quartz grains and finer feldspars and micas, will decompose into a coarse sandy clay material, the coarser components being derived from the quartz fraction, and the finer fraction being linked to the weathering of feldspars and micas. The granite areas in South Africa weather into yellow-brown sands on the middle slopes and yield highly leached and acid white (albic) sands in the lower landforms. Basic igneous rocks like basalt will decompose into fine material. They form into red clayey soils on well-drained slopes (because they contain a lot of iron bearing minerals) and into Vertisols on lower flat slopes. For carbonaceous rocks the particle size distribution of the weathering material will mainly depend on the nature and composition of the acid insoluble residue, though in most cases it will hold a clayey texture.

Coherence and hardness - The coherence and hardness of the parent rock determines the type of weathering and affects the speed by which the bedrock decomposes into loose material. Soft substrata like chalky limestone or marl are easily broken down and their weathering material consists of coarse fragments that reflect closely the mineralogical composition of the parent rock. Moreover, the landscape on these rocks is severely eroded, soils are constantly rejuvenated and remain skeletal.

On more coherent carbonaceous substrata the physical disintegration of the rock is slower and, simultaneously with a mechanical breakdown, an initial chemical weathering of the soil material takes place. The harder and compacter the limestone the more difficult and slower is the physical rock weathering, but over this longer period also chemical processes can start. The volume of weathering material produced is small (to the point that it is often limited to a fine weathering cortex which is hard to observe with the naked eye), but it has already undergone a relatively important physicochemical and mineralogical transformation. In the field this is reflected in a clear-cut differentiation between the (white) rock and the partly or completely decalcified (red) soil.

Permeability and water infiltration - The permeability of the solum determines how much water and at what speed it can percolate through the profile and, therefore, affects the intensity of the chemical reactions and leaching.

A soft limestone and marl behave completely different in terms of permeability and water infiltration than a fractured hard limestone. The former is rapidly saturated after the first winter rains and remains almost impermeable for the rest of the season. Vertical water percolation and leaching in these soils is therefore seriously restricted, and enhances lateral runoff and surface erosion; in flat areas with no runoff, soils remain saturated with water for some time of the year and get hydromorphic properties.

On hard limestone the situation is different, in the sense that the rock, although rather impermeable by itself, is generally interwoven by many cleavages, joints and dissolution holes through which rainwater infiltrates (Photo 1). Leaching is therefore activated, and easily soluble soil components (in this case mainly calcium- and magnesium carbonates) are evacuated from the profile. At the same time, pH decreases and the non-carbonate fraction undergoes further weathering as well. Soil formation on hard limestone yields therefore less weathering product but it is more intensely weathered than on less permeable carbonaceous substrata. The intensity by which leaching processes take place in the profile depends on the amount of water that passes through the soil (rainfall regime) and to the permeability of the substratum.

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Photo 1. Nature of hard limestone with numerous joints and dissolution holes, allowing the water to infiltrate into the soil substratum.

2.3. Time

Physical and chemical weathering processes are often slow and it takes time before their effects become visible. Time as a soil forming factor is, therefore, closely related to the combined effect of climate, parent material and human activity. The longer the time chemical weathering, leaching and clay migration can operate in a soil, and the less the soil is affected by erosion or by Man, the more advanced will be its development.

The study of the time factor automatically implicates the evaluation of soil age, as well in the absolute as in the relative sense. In this respect, there exist two schools of thought, e.g. those who consider Mediterranean soils as a paleo-formation, and those who believe that they are the result of present-day environmental conditions.

Main promoters of the paleo-formation theory were Reifenberg (1947), Kubiena (1953) and Durand (1959). These authors believed that Mediterranean soils are mainly relict soils which have formed and developed under much moister tropical and subtropical climates of the late Tertiary and early Pleistocene periods. Although it may not be excluded that some of these soils have initially been formed at that period or at least under somewhat moister conditions than the present, studies by Lamouroux (1971) and Verheye (1973) in Lebanon have illustrated that their genesis is still active today, and that they can be considered as being in equilibrium with the present-day prevailing Mediterranean climate.

The question of the age of Red Mediterranean Soils is still unsolved, and most probably both theories hold a basis of truth. In this respect, Torrent (2004) refers to the intrinsic mosaic of Red Mediterranean soils observed in Spain and formed on both Pliocene *ranas* and Lower Pleistocene surfaces, represented by different pediments and river terraces,

2.4. Topography

In contrast with climate and parent material which exercise an active role in soil formation, topography is a passive element which refrains or orients profile development within the context determined by the former factors. Moreover, the exposure of slope with respect to rainfall and sunshine interception leads to different pedoclimates and weathering conditions on sun-exposed slopes (where evaporation is more intense and less soil moisture is available for weathering and leaching) as compared to slopes facing away from the sun.

In a steeply dissected landscape part of the rainfall runs along the slopes and creates erosion. Surface layers are removed, the deeper unaltered layers are brought nearer to the surface, and the profile is "rejuvenated". The soil remains shallow and skeletal.

On more or less flat topography, lateral runoff is reduced and the rainwater will either percolate through the soil and underlying rock or it will stagnate on an impermeable deeper layer. In the first case it will stimulate weathering, deepen the profile and develop a better structure. Obviously, the soil which develops under those conditions will display physicochemical and mineralogical properties which differ from the underlying rock. In soils developed over carbonaceous substrata this is reflected in a more or less important decrease of the free $CaCO_3$ content in the upper layers, an initial clay migration into depth and the development of a good (sub)angular blocky structure in the subsurface horizons. In erosion-protected areas developed over hard permeable limestone soil development moves into a more or less de-calcified brown to reddish-brown soil (corresponding to Kubiena’s *Terra Fusca*, or to the *Inceptisol-intergrade-Alfisol* stage of Soil Taxonomy) or to a red completely de-calcified profile (corresponding to Kubiena’s *Terra Rossa* or Soil Taxonomy’s *Alfisol* stage).

In the second case, soil water will stagnate over an impermeable layer and profile development will be hampered under these temporary hydromorphic conditions. When the weathering product holds high amounts of swelling clays, vertic properties may develop.

Soil material eroded in the uplands accumulates in the lower parts of the landscape. Alluvial plains and their contiguous terraces extend over tens of kilometers in the major river valleys. River terrace soils provide an excellent soil chronosequence over long periods, extending sometimes until the Quaternary. Some of these terraces reach heights of more than 200m above the present river channel, as is the case in the Guadalquivir valley in southern Spain.

The role of topography in a Mediterranean environment is thus mainly to promote or inhibit normal soil development through its influence in the rejuvenation or protection of some landscape positions and in the accumulation of soil material and water in others.

2.5. Biological Activity and Man

The areas around the Mediterranean Sea have been densely populated and intensively exploited for long periods in history, and therefore human influence on soils and soil properties is immense. The most critical actions in this respect involve crop production, deforestation, grazing and related practices. In the New World, i.e. California, Chile, South Africa and Australia, this influence is obviously much less visible.

Massive *deforestation* in almost all the areas around the Mediterranean Sea is reported in almost all archives. Greece and Lebanon were major providers of timber for ship building and fuel wood in the eastern Mediterranean. Deforestation and *wildfires*, linked to traditional grazing practices, or modern land speculation are still an annual event in Italy, France, Spain and Portugal *(see also: Drylands and Desertification)*.

The abrupt elimination of the vegetation leads to erosion of the surface layer and soil "rejuvenation". The elimination of the natural surface cover through deforestation, overgrazing or burning also modifies soil microclimate and affects indirectly biological activity in the soil. Variations in microclimate, and particularly in the soil moisture status, affect the intensity of physicochemical weathering and mineralogical transformations. Field observations have shown that under a dense vegetative cover soil pH variations may exceed more than 1 unit between winter and summer periods as a result of the varying plant activity and CO_2 production.

An indirect effect of human activity is reflected in climate change, which is believed to result in an overall deterioration of soil quality in Mediterranean regions. A recent European study (EEA, 2003) has indicated that possible effects include salinization, organic matter loss and increased wind and water erosion. Forest soils face already a loss of carbon through wildfires. As these are likely to increase, adapted policies should be developed to preserve soil quality and to promote a more sustainable use of land, for example through afforestation.

3. Pedogenesis and Profile Development

The combined effect of the soil forming factors described above leads to a gradual disintegration and decomposition of the parent rock into a loose weathering product, with characteristics that progressively differ from those of the parent material. This differentiation increases with the amount of water that enters the soil, i.e. with a higher rainfall intensity and soil permeability.

The primary and most visible change consists of a mechanical and physicochemical breakdown of larger rock fragments into finer components. In soils developed over limestone and related carbonaceous rocks this process is mainly associated with a progressive decalcification, a decrease of the soil pH towards neutrality, and a slight clay migration into the subsurface layers. On other non-calcareous substrata the decalcification phase is skipped and soil formation starts immediately with a chemical attack of the less stable primary minerals under acid pH conditions, in particular feldspars and micas, and their re-crystallization *in situ* or migration into the deeper layers.

Overall, weathering and soil formation in a Mediterranean climate show similar trends as observed in the subhumid tropics with summer rainfall, but with the major difference that they act at a much lower intensity. Where parent material, time and topography allow, the result is a (more or less decalcified), well-structured reddish-brown to red profile, characterized as Red Mediterranean Soil or *Terra Rossa*. This type of soil is less weathered and leached than (sub)tropical soils, and is characterized by:

- a moderately deep soil profile with a more or less well-defined clay illuviation in the subsoil;
- a rather prominent dissolution and leaching of carbonates and other easily soluble components;
- the development of a characteristic red matrix color, often identified as *rubéfaction* in French literature;
- and a colloidal complex which is almost completely saturated by bivalent cations.

Obviously, not all Mediterranean soils reach the red stage described above, mainly because their normal evolution is hampered either by erosion (and rejuvenation) of the profile, and/or because the parent material is too poor in iron, rainfall is too low, or time has been too short to allow for a complete decalcification and *rubéfaction*.

3.1. Pedogenesis on Carbonaceous Rocks

Carbonaceous rocks are the most important parent material in Mediterranean areas. Though they are dominated by a relatively soluble $CaCO_3$ fraction, the soils developed on them may well differ due to differences in coherence, permeability and resistance to weathering of the substratum.

The characteristic feature of soils developed over limestone is the overall presence of an important amount of $CaCO_3$ and (to a lesser extent) of $MgCO_3$. The first step in the pedogenetic evolution of these soils is therefore the dissolution and leaching of $CaCO_3$ from the solum, the intensity of which is affected by: (1) the dissolution speed of the carbonate fraction, (2) the amount of (rain)water that infiltrates the soil, and (3) the initial $CaCO_3$ content of the soil and the substratum. The pedogenetic evolution may, however, be quite different on (impermeable) marls or soft, marly limestone than on (more permeable) hard, compact and often dolomitic limestone holding many joints and dissolution holes.

Field observations have indicated that there is a direct relation between the progressive decalcification of a soil - and thus its development stage - and its color: the more decalcified and thus the more mature the profile, the redder becomes its matrix color. The various steps in the pedogenesis of Mediterranean soils on limestone can therefore be associated with a color sequence including an initial grayish-white stage, followed by a brown (ranging from yellowish-brown to reddish-brown) intermediate maturity stage, and ending with a red mature development stage (Figure. 2).

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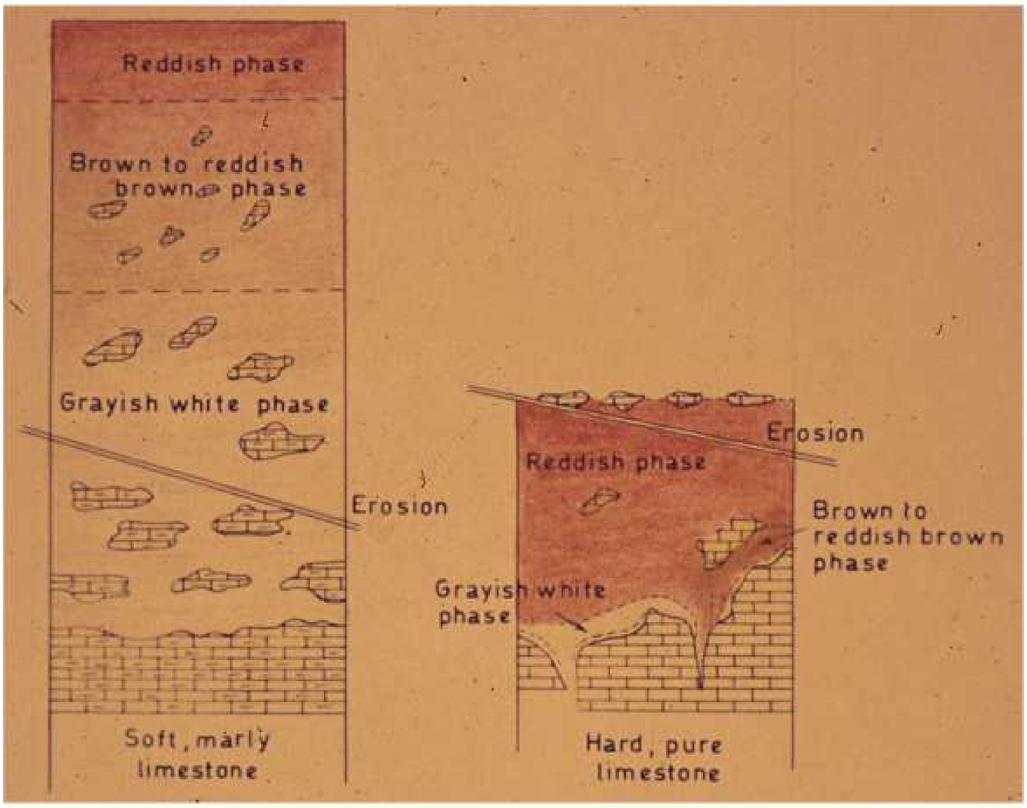

Figure 2. Schematic representation of the pedogenetic evolution on limestone in a Mediterranean environment. An example from Lebanon (Verheye, 1973).

Grayish-white phase **-** Weathering starts with the gradual physical disintegration of the substratum into a loose material, that mineralogically and physico-chemically shows almost no difference with the unaltered rock. The intensity by which the $CaCO_3$ fraction is dissolved is directly influenced by the hardness of the rock and the aggressiveness of the climate.

A second factor influencing this process is the mineralogical composition of the bedrock, in particular its acid insoluble fraction. On soft and impure limestone and marl the acid insoluble residue is in the order of 10-15 weight%, and this makes that the remaining soil volume after dissolution of the $CaCO_3$ fraction will be higher than on pure hard limestone, where the non-carbonate fraction is generally less than 3%.

On ***soft limestone and marl*** weathering is fast, and the grayish-white lithomorphic A-C or A-R profile on top is mainly the result of a quick mechanical disintegration of the substratum. Chemical weathering and other soil-forming processes are not very active, as expressed by the almost undifferentiated $CaCO_3$ profile and the weak increase of free Fe_2O_3 (Soil A, Table 1). Microscopic observations of the soil layers show an overall dense micritic (micro-crystalline calcite) soil matrix, with local areas of a partial dissolution and re-crystallization of calcite, generally under the form of ***lublinite*** (Photo 2). This needle-shaped calcite mineral is characteristic for the re-crystallization of calcium in a temporarily slightly acid environment occurring during part of the year along active drainage channels in the soil.

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Photo 2. Needle-shaped lublinite crystals concentrated in voids.

Table 1. Analytical characteristics in a representative soil color sequence on carbonaceous rocks from South Lebanon (Verheye, 1973).

Profile	Color (Munsell)	Clay %	pH (water)	$CaCO_3$ %	Free Fe_2O_3	Base saturation
A: Grayish-white phase on soft limestone (A-C profile)						
A (0-25 cm)	10YR 8/1	33.5	8.4	80.0	0.60	100
C (25-40cm)	10YR 7/2	36.4	8.5	77.5	0.67	100
R (40cm+)	10YR 8/1	-	-	92.0	0.15	100
B1: Brown phase; (B) pocket in grayish-white soil						
A (0-20 cm)	10YR 8/1	37.5	8.5	78.0	0.57	100
(B) (20-42cm)	7.5YR 4/3	41.2	8.5	68.5	0.90	100
C (42-75cm)	10YR 6.5/2	44.1	8.6	71.5	0.86	100
R (75 cm+)	10YR 8/1	-	-	92.0	0.15	-
B2: Brown phase: Yellowish-brown soil on chalk (A-(B)-C profile)						
A (0-10 cm)	10YR 5/5	36.5	8.6	29.0	4.21	100
(B) (10-35cm)	10YR 5/4.5	50.1	8.5	29.5	3.50	100
BC (35-55cm)	10YR 5/4	49.6	8.5	30.0	3.54	100
Cca (55-60cm)	10YR 8/1	-	-	50.5	2.05	-
R (60 cm+)	-	-	-	91.0	-	-
B3: Brown phase: Reddish-Brown soil on hard compact limestone (A-B-C profile)						
A (0-15 cm)	5YR 3/4	71.4	8.1	0	9.07	100
B2t (15-40cm)	5YR 3/4	76.5	8.0	4.5	9.26	100
BC (40-80cm)	5YR 4/6	72.8	8.4	16.0	8.00	100
C1: Red phase: Terra Rossa on hard limestone on erosion-protected surfaces (A-Bt-C)						
A (0-15 cm)	2.5-5YR 3/4	80.5	6.9	0	9.50	92
B1t (15-6(cm)	2.5-5YR 3/4	82.4	6.6	0	9.95	95
B2t (65-100cm+)	2.5-5YR 3/4	86.7	6.7	0	15.95	95

On ***hard, compact limestone*** the dissolution speed of the carbonates is much slower and the acid insoluble residue is much smaller (Figure 2). Hence, on this substratum shallow stony soils embedded in a whitish calcareous loose soil material as observed on softer limestone, are not found. This is because the soil volume of grayish-white material as described above, is limited to a very fine weathering cortex of a few mm. thick, and often not well observed with the naked eye. Table 2 provides analytical data of the contact zone between such hard limestone and the *Terra Rossa* which has developed on it. The section corresponding with the grayish-white phase in this sequence corresponds to the weathering cortex stage 2.

Brown Phase - The brown phase corresponds with a slightly advanced evolution stage of the weathering material. In this phase three grades can be differentiated (Table 1, profiles B1, B2 and B3), depending on the intensity by which $CaCO_3$ is leached.

Phase B1 is only occasionally observed in pockets of grayish-white soils where the permeability of the underlying rock is somewhat better, and where erosion is not strong enough to continuously rejuvenate the soil (Photo 3). The profile (Table 1, Soil B1, pocket between 20 and 42 cm depth) is moderately deep, holds less rock fragments and displays an A-(B)-C horizon sequence with a weakly structured cambic-B horizon, a slight but obvious $CaCO_3$ leaching, and a slight accumulation of free Fe_2O_3 in the decalcified zone.

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Photo 3. Development of a pocket of brown soil with A-(B)-C profile in a surrounding environment of grayish-white soils, South Lebanon.

Phase B2 (Table 1) is observed on moderately coherent and slowly permeable substrata like chalk or moderately soft limestone. In contrast with the former situation whereby the brown color was limited to small pockets in the soil, the brown to yellowish-brown color is now more uniform over the profile. It is associated with a prominent leaching of $CaCO_3$ in the upper horizons, with free lime contents around 30%, and a Ca-accumulation below. The free Fe_2O_3 content attends between 2 and 4% in the partly decalcified parts of the profile.

This partial decarbonization is reflected under the microscope by a partial but incomplete disappearance of the crystic soil fabric masking an underlying yellowish brown plasma, and intersected by a few calcite grains and other structures inherited from the underlying parent rock. One notes also the presence of lublinite crystals (Photo 2) in voids around partly decalcified areas.

In the third phase, expressed by Profile B3 (Table 1) the soil matrix turns into a definite reddish-brown color. It is observed on a relatively compact, moderately permeable limestone substratum with many joints and dissolution holes (Photo 1). The soil on top of this parent material is relatively well drained though, as a result of its clayey texture, its internal drainage may be slow. Hence, most $CaCO_3$ is leached and is evacuated from the profile, and the increase of free Fe_2O_3 is prominent. Goethite is generally the dominant iron compound *(see also Soil Microscopy and Micropedology)*

Many soils of the karst landscape on hard limestone in the eastern Mediterranean area have reached this stage. They correspond to the so-called *Terra Fusca* soils of Kubiena (1953), which considered them as an evolution stage towards *Terra Rossa*. In Lamouroux's sequence (Table 2), they correspond to the weathering cortex-stage 3. They can also be observed as brown pockets within *Terra Rossa* soils (see below) located under larger stones or along side walls of the dissolution holes, where normal water percolation - and thus decalcification - has been incomplete. This corresponds to what Lamouroux has called the Red Transition Zone (Table 2, stage 4).

Table 2. Analytical characterization of the five consecutive weathering stages on hard limestone in Lebanon (Lamouroux, 1971).

Sample →	**Fresh rock**	**Weathering cortex**		**Red transition zone**	***Terra Rossa***
Soil property ↓	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**	**Stage 5**
Color	10YR7/2	10YR4/6	7.5YR5/6	5YR4/6	2.5YR3/6
Apparent density	2.68	2.47	-	-	-
%$CaCO_3$	98.0	82.0	61.0	39.7	0
% Free Fe_2O_3	0.13	2.32	3.74	7.17	14.7

Red Phase **-** The third and last evolution stage in this color sequence is the result of a slow and prolonged weathering, and is expressed by a red (2.5YR - 5YR) deep soil with an A-Bt-C profile often developed in the joints and dissolution holes of hard limestone in a karst landscape (Photo 1). It corresponds to the *Terra Rossa* of Kubiena (1953), and can be associated with Phase 5 in Lamouroux's weathering sequence (Table 2). In the field it is almost exclusively observed on hard permeable limestone and in topographic positions which are not affected by erosion nor by rejuvenation processes.

As a result of the intensive physico-chemical evolution of the profile the red soil material differs completely from the original parent rock (Table 1, Soil C1). Besides a total decalcification, associated with a decrease of the soil pH near to neutrality and a tendency towards a slight desaturation of the base complex, one can observe an important enrichment of iron compounds (10% and more) and an obvious clay illuviation reflected in the presence of clay skins on the structural elements.

Under the microscope the crystic fabric has completely disappeared and the plasma is composed of a red-brown ground mass of clay and iron oxihydrates, with a characteristic striated orientation pattern.

The mineralogy of the clay fraction confirms the overall presence of 2:1 clays in both the acid insoluble fraction of the parent rock and the soil, though there is a tendency to a relative accumulation of quartz, iron compounds (goethite and hematite) and even kaolinite in the soil layers. It is not clear whether this accumulation is due to a relative increase of inherited components from the rock or if a neo-synthesis of kaolinite has taken place. Obviously, for the latter process to happen the overall soil pH in most of these soils is still too high, though there exist remnants of well protected soils where pH values are below neutrality (Table 1, C1 soil). A neosynthesis of kaolinite involves thus that as a result of seasonal fluctuations in soil acidity the pH should have dropped to levels around 6.0 which seems only plausible under conditions of slightly higher than actual rainfall.

The relatively long period needed to attend this reddish evolution stage, explains why *Terra Rossa* units occur only on flat and erosion-protected surfaces developed over hard permeable limestone. Under the actual environmental conditions in the Mediterranean basin this weathering stage is never reached on soft, marly substrata because of the permanent rejuvenation of the solum (Figure 2). The occasional development of a brown to dark-brown horizon in some profiles developed over softer limestone and the more general occurrence of dark reddish-brown profiles on somewhat better drained chalky limestone illustrate this finding. In other words, *Terra Rossa* soils reflect a profile which under the actual climatic conditions corresponds with the maximal attainable development stage in this sequence, but as soon as environmental conditions are no more optimal, this red phase is not reached.

Pedogenesis under temporary hydromorphic conditions - Some parent materials like marls are almost impermeable for water because, besides calcium carbonate, they include an important amount of (expanding) clay in their non-carbonate fraction. After the first winter rains marl soils are therefore rapidly saturated with water, and this enhances erosion of the topsoil and the creation of a characteristic landform known as badlands. In a flat topography however, affected by little or no erosion, the soil saturation in winter alternates with dry summer conditions, and this leads to the development of vertisol properties.

In the field these soils display a moderately deep A-(B)-C-R or A-(B)-R profile, with a rather fine texture, generally dominated by expanding clays, a moderate $CaCO_3$ leaching, and a well developed subangular blocky structure tending in the deeper horizons towards a prismatic type. They have characteristic properties like surface cracks in summer, a weak gilgaï micro-relief, and *slickensides* on the structural elements in the subsurface layers.

The physico-chemical properties of these soils are dominated by a clear but incomplete $CaCO_3$ movement in the soil, a high pH and a completely saturated base complex. As compared to the grayish-white soils calcium carbonate is leached and the Fe_2O_3 content has quite substantially been increased. Despite their surprisingly low organic carbon (OC) content, they maintain a very dark color throughout the profile. This indicates a strong binding of OC on the clay complex and an incorporation of this OC in the crystal lattice, as has been observed in *regurs* in India, *tirs* and *tirsified soils* in Morocco and black tropical clay soils in general.

3.2. Pedogenesis on Non-Carbonaceous Rocks

On other non-carbonaceous rocks like basalt, shale, granite, gneiss, quartzite or sandstone, there is no need for a decalcification of the weathering material (white phase), and the initial development stage is formed by a shallow skeletal soil, dominated by rock fragments which are not more than products of the physical breakdown of the underlying substratum. The color of the soil in this case is a direct reflection of the hue of the parent material, i.e. dark hues for soils developed over basalt, yellowish hues on shale, grayish-white hues on granite and gneiss.

The second weathering phase, corresponding to the *Brown Phase* in the color sequence on calcareous parent materials is represented by a moderately deep ABC profile, the major characteristics of which are: the presence of a textural B horizon, a poor reserve in weatherable minerals, low cation exchange capacity and relatively high base saturation. The soil pH is acid in the surface layers, but increases with depth. This weathering type has been described as *Braunlehm* (Kubiena, 1953) or as intermediate between *Braunlehm* and *Terras Pardas* (Cardoso, 1965). On level plains they develop into *Para Hydromorphic soils* and *Planosols* (Cardoso, 1965).

Red Mediterranean soils on non-calcareous materials (being distinguished here from Terra Rossa which are linked to a limestone substratum) form the third and final weathering stage on these materials. They have an ABC profile, and their major edaphic characteristic is the presence of a textural B horizon with a deep red color and a relatively low base saturation. In earlier literature they were often described as *Rotlehms* (Kubiena, 1953). This type of soil is also characteristic for the *ranas* formations, which cover more than 10,000 km^2 in Spain only. These are sedimentary formations of Pliocene age, several meters thick and including fragments of quartzite, schist, serpentine embedded in a reddish clay or sandy clay soil mass; they include often iron crusts, known locally as *ferruginosas.*

4. Classification

Mediterranean soils are classified differently in the various world classifications depending on the selection and relative importance given to the criteria differentiae, the definition of diagnostic properties and taxa, and the objectives of the system. In this section the position of Mediterranean Soils in the 3 major world classification systems is discussed.

4.1. USDA Soil Taxonomy

The American Soil Taxonomy (USDA, 1975 and updates until 2003) is a pragmatic classification system based on well-defined diagnostic horizons and properties. It is a hierarchical system ranking soils from a higher to lower level into Orders, Suborders, Great Groups, Subgroups and a number of lower categories (Families, Series and Phases). Mediterranean soils do not have special differentiating diagnostic horizons or morphological, physical or chemical properties that set them aside from other soils, but are mainly characterized by pedo-climatic features, e.g. soil temperature and soil moisture regimes, which interfere only at lower levels. Hence, Mediterranean soils are not differentiated at the Order (level 1), but at the Suborder and Great Group levels (levels 2 and 3).

In the USDA system Mediterranean soils are characterized by a xeric moisture regime. In this regime the soil moisture control section is dry in <u>all parts</u> for 45 or more consecutive days within the 4 months that follow the summer solstice in 6 or more years out of 10. It is moist in all parts for 45 or more consecutive days within the 4 months that follow the winter solstice in 6 or more years out of 10. The moisture control section is moist in <u>some part</u> more than half the time, cumulative, that the soil temperature at a depth of 50 cm is higher than 5°C, or in 6 or more years out of 10 it is moist in some part for at least 90 consecutive days when the soil temperature at a depth of 50 cm is continuously higher than 8°C. In addition, the main annual soil temperature is lower than 22°C, and mean summer and mean winter soil temperatures differ by 5°C or more at a depth of 50 cm or at a lithic or paralithic contact, whichever is shallower.

Mediterranean soils are found back at suborder level (level 2) in six orders, viz. Andisols, Alfisols, Inceptisols, Mollisols, Ultisols and Vertisols. They are identified by the prefix "xer" coupled to the formative element for the specific order, e.g. as Xeralfs or Xererts in Alfisol and Vertisol orders respectively. In Entisols they are only distinguished at great group level (third level), being identified by the prefix "Xer" or "Xero" coupled with the formative element for the specific suborder.

The most commonly encountered Mediterranean soils are qualified as Xeralfs, Xerolls and Xererts. Soils which are more or less affected by erosion and accumulation processes qualify as Xerepts (within the Order of Inceptisols) or as Xerarents, Xeropsamments, Xerofluvents or Xerorthents (as part of the Order of Entisols and Suborders of Arents, Psamments, Fluvents and Orthents). Mediterranean soils that have developed on volcanic ejecta are classified as Xerands (as part of the Andisol Order).

Xeralfs are Alfisols, i.e. well developed soils with a clay illuviation (argillic, natric or kandic) horizon, high base saturation, and an epipedon that is both massive and hard when dry. They are relatively extensive in Mediterranean regions of the USA, Chile, South Africa and around the Mediterranean Sea. They are further subdivided at Great Group level on the basis of characteristics (like color, etc.) or diagnostic horizons (like the presence of a hard impermeable layer, etc.).

Xerolls are Mollisols, i.e. mineral soils with relatively thick, dark-colored, humus-rich surface horizons, dominated by bivalent cations and a good, stable structure. They have thinner, lighter-colored topsoils or lower lime contents than the typical Mollisols of the temperate grasslands on loess. Xerolls are not extensive, worldwide, but cover important surfaces in parts of Turkey, Northern Africa near the Mediterranean Sea, and in Washington, Oregon and Idaho states in the USA. Six Great Groups have been recognized with the Xerolls.

Xererts are Vertisols with a high clay content (swelling clays), shrink-swell properties, and wide cracks in the dry season. *Calcixererts* have a high (petro)calcic horizon within 100 cm from the surface. All other Xererts are classified as *Haploxererts.*

The basic principles of USDA-Soil Taxonomy and various classes up till subgroup level are explained *in extenso* in USDA (1975). Details on the latest updates of the classification can be found in Soil Survey Staff (2003) and http://soils.usda.gov/technical/classification/taxonomy

4.2. World Soil Reference Base for Soil Resources

The World Reference Base for Soil Resources (WRB) is the result of a cooperative project between the International Union of Soil Sciences (IUSS, formerly International Soil Science Society), the Food and Agriculture Organization of the United Nations (FAO) and the International Soil Reference and Information Centre (ISRIC). In 1998 the IUSS accepted it and recommended that it should be used as a reference classification through which national soil classification systems should communicate with each other. The WRB is in the first place a reference base and a common denominator with a function to stimulate harmonization and correlation of existing national systems. It is now the most universally used classification.

The WRB system was developed from the legend of the FAO-UNESCO Soil Map of the World, which was first published in 1974 and thereafter revised several times, up to the publication of the last revision in 1988. Like Soil Taxonomy and the FAO system, the WRB system is based on well-defined diagnostic horizons and properties as differentiating criteria. Many of these have the same nomenclature and definitions as their counterparts in Soil Taxonomy. The system has 30 Reference Groups as the highest category of classification. Each reference group is provided with a listing of possible qualifiers in a priority sequence from which the user can construct the various lower level units. The broad principles which govern the WRB class differentiation are (FAO/ISSS/ISRIC, 1998):

- at the higher categoric level, classes are differentiated mainly according to the primary pedogenetic process that has produced the characteristic soil features, except where special soil parent materials are of overriding importance, and
- at the lower categoric levels, classes are differentiated according to any predominant secondary soil forming process that has significantly affected the primary soil features; in certain cases soil characteristics that have a significant effect on use may be taken in account also.

Though a number of Reference Soil Groups may occur under different climatic conditions, it was decided not to introduce climatic parameters in order to avoid that the classification of soils would be subordinated to the availability of climatic data. Soils from 21 of the 30 WRB reference groups are represented in Mediterranean regions. Reference groups that are not represented are those from the cold polar regions and highly weathered humid tropics, as well as some from the temperate higher latitudes. Of the approximately 422 million ha of Mediterranean soils, Calcisols (85 Mha), Cambisols (68 Mha) and Luvisols (65 Mha) are the WRB reference groups occupying the largest areas.

Calcisols are characterized by a prominent translocation of calcium carbonate from the surface horizons into a soft, powdery or hard accumulation layer at some depth in the profile. Most Calcisols are well drained, and have an ochric surface horizon, a medium to fine texture and a good water holding capacity.

Cambisols are moderately developed soils with an A-(B)-C profile, characterized by a slight or moderate weathering of the parent material, and by the absence of appreciable quantities of accumulated clay, organic matter, aluminum or iron compounds. Cambisols develop generally on medium and fine textured material derived from a wide range of rocks.

Luvisols are soils with a clay illuviation from the surface soil to an accumulation horizon at some depth; they have a high base saturation, and a relatively important nutrient content. They generally cover flat or gently sloping land and can be considered as a soil type in equilibrium with the present environmental conditions. In areas where erosion is active they are generally associated with Cambisols.

Reference soil groups of less importance, with their Mediterranean Soil Taxonomy equivalents in brackets, are:

- Leptosols, shallow, often gravelly and erosion-prone soils, with a limited soil volume and therefore subject to both drought and waterlogging (formerly Xerochrepts, now Dystro or Haploxerepts).
- Kastanozems, soils of the drier Mediterranean areas, with a mollic horizon and containing secondary calcium carbonates in the subsurface layers (Xerolls).
- Arenosols, coarse textured infertile soils developed over sandy parent materials or wind-blown sands (Xeropsamments).
- Regosols, shallow soils with a low-humus surface horizon overlying directly the weathering rock in an actively eroding landscape (some Xerorthents).
- Planosols, soils with an abrupt textural break within 100 cm from the surface, affecting seriously the moisture status of the root zone (Aqualfs).
- Vertisols, fine textured soils dominated by swelling clays and presenting cracks after drying, while being sticky and plastic when wet (Xererts).
- Fluvisols, lowland soils developed in recent fluviatile, lacustrine or marine deposits, showing commonly stratified layers and an irregular distribution of organic matter with depth (Xerofluvents).
- Acrisols, highly weathered soils developed under moist aggressive leaching conditions, with an argillic horizon and a base saturation below 50%; probably paleosols inside the present Mediterranean environment (Xerults).
- Solonchaks, saline soils developed over marine intrusions or in inland basins affected by saline seepage (saline soils of different orders).
- Solonetz, soils with natric horizons (Natrixeralfs).
- Andosols, soils developed in volcanic ejecta (Xerands).

More detailed information on the WRB system can be found in (FAO-ISSS-ISRIC, 1998), Driessen *et al*. (2001) and Nachtergaele (2004), or on the website http://fao.org/landandwater/ agll/wrb/wrbdocs.stm

4.3. French CPCS Classification

The taxonomy proposed by the Commission of Pedology and Soil Cartography (CPCS, 1967) is an outgrowth of an earlier classification of Aubert and Duchaufour. The higher categories of the French taxonomy are the class (level 1), subclass, group and subgroup (levels 2 to 4), and these correspond often, though not always, to the main categories of USDA-Soil Taxonomy and the WRB systems. The difference with the former systems is that the French classification is mainly based on pedogenetic criteria, and thus more on concepts than on hard analytical data, whereby these concepts are not always expressed in clear quantitative differentiations.

The majority of soils of Mediterranean areas belong to 4 main classes of the French CPCS system:

- Class I: Sols Minéraux Bruts, sous-classe Non-Climatique, which regroups recent, skeletal soils with an A-C profile, developed either on hard consolidated rocks on an erosion surface (group: Sols Minéraux Bruts d'érosion, subgroups Lithosols or Regosols) or in the lower parts of the landscape (Sols Minéraux Bruts d'Apport Alluvial ou Colluvial), or in aeolian accumulation zones (Sols

Minéraux Bruts d'Apport Eolien). A fifth group characterizes the man-made soils (Sols Minéraux Bruts Anthropiques).

- Class II: Sols Peu Evolués, sous-classe Non-Climatique. These characterize relatively young soils with an A-C profile covered by a well developed humus layer. It includes the same 5 soil groups as described for class I.
- Class V: Sols Calcimagnésiques. These are characterized by an A-C or A(B)C profile with no prominent clay illuviation, a high base saturation dominated by Ca^{2+}, and a neutral to slightly alkaline pH. Fragments of unaltered $CaCO_3$ may still be present in the profile. Most Mediterranean soils belong to subclass V-1: Sols Carbonatés, Groupes Rendzines or Sols Bruns Calcaires. Soils of this class V developed under a higher rainfall regime may occasionally be classified in subclass V-2: Sols Saturés, groupes Sols Bruns Calciques, Sols Humiques Carbonatés or Sols Calciques Mélanisés.
- Class IX: Sols à Sesquioxides de Fer, sous-classe IX-2: Sols Fersiallitiques. This unit groups the red, almost decalcified Terra Rossa soils with high base saturation and neutral to slightly acid pH. Two groups can be recognized:
  - Sols Fersiallitiques à réserve calcique, generally poorly leached;
  - Sols Fersiallitiques sans réserve calcique, often leached.

There exist also many intergrades between the Soil Fersiallitiques (class IX-2) and the Sols Calcimagnésiques (class V) and even with the Sols Bruns Eutrophes (class VII). Additionally, soils of minor importance may classify in the following units: Vertisols (class III), Sols Isohumiques (class VI) and Sols Brunifiés (class VII).

The traditional CPCS system has been subject to a number of critical reviews. There is now a tendency, though not fully accepted, to abandon the CPCS system in favor of the new Référentiel Pédologique (Baize and Girard, 1995). The CPCS classification is, however, still widely used in France and in former French colonies in Africa.

5. Land Use and Production Potential

5.1. Natural Vegetation

The natural vegetation in the areas bordering the Mediterranean Sea consists of holm oak (*Quercus ilex*), cork oak (*Q. suber*), wild olive (*Olea europeae*), carob (*Ceratonia siliqua),* lentisk (*Pistacea lentiscus*), stone pine (*Pinus pinea*) and Aleppo pine (*P. halepensis*). Degradation of the original forest often results in the establishment of a thorny xerophytic vegetation, called guarrigue (garriga in Spain) on calcareous soils or maquis (macchia in Italy) on acid soils.

The present day natural garrigue or maquis vegetation consists of a prickly and thorny vegetation with stunted evergreen oaks, and a profusion of aromatic species of lavender, myrtle, oleander and other spiny and sclerophytic shrubs able to reduce evapotranspiration demands in summer. Remnants of true forests are concentrated in the more rainy parts of the region, and are then often composed of trees with a deep rooting system.

In North America, the forests of western California are similar to those of the Mediterranean basin, and a formation similar to the maquis is named chaparral. In South America, the Chilean forest holds species such as *Quillaja saponera*, *Rhus caustica* and *Pneumus boldus*. In South Africa the fynbos vegetation from the Cape region includes, inter alia, protea and erica spp. The characteristic natural vegetation in Southwest Australia are the jarrab and wandoo forests, consisting basically of *Eucalyptus* species like *E. marginata* and *E. redunca*.

The commercial exploitation of some native species has led to the development of the perfume industry around the city of Grasse in France, the export production of Protea in South Africa, and many other uses.

5.2. Crop Production

The agricultural production potential of Mediterranean areas is determined by the length and importance of the winter rainfall, the tolerance of plants to overcome the summer moisture stress (or to limit their growth cycle to the period of water availability), and the intrinsic soil quality.

The climatic characteristics of Mediterranean areas have been described and commented above. Thomas (2005) argues that the intrinsic soil quality of Mediterranean soils is more influenced by physical than by chemical properties. Soil texture is an important factor, particularly because it affects the moisture retention of the profile and, thus, may extend the length of the moisture available period for the crop. In this respect clayey and deep soils are more suited for crop production than sandy and/or shallow profiles. Stoniness is widespread and has a negative effect on crop production because it hinders root development and reduces water retention. However, surface stoniness helps reduce surface evaporation, protects soil against splash erosion and delays runoff. Surface stoniness, associated with the presence of numerous rock outcrops, makes that mechanized agricultural operations are often difficult. Surface crusting affects soils rich in silt and fine sand, hindering emergence of small seedlings, reducing soil infiltration and triggering runoff.

In terms of soil chemical properties, Mediterranean soils compare favorably with soils of other geographic regions. Cation exchange capacity and base saturation are generally high, except on very acid rocks. Most soils are also responsive to fertilization with P, are well supplied with K because of their high illite content, and contain adequate levels of Ca and Mg. However, Fe, Cu, Mn, Zn and B deficiencies arise frequently in calcareous soils. In irrigated land salinization may become a major problem, mainly in areas where good quality water is scarce and water-saving systems are applied.

Amongst the cultivated perennials there are few trees like olives, figs, almonds and pistachios, as well as grapes which are able to survive under Mediterranean rain fed conditions without damage. In all other cases agriculture has to concentrate on annual crops with a growing period that corresponds in length and moisture requirements with the rainy winter season, or that relies on supplementary irrigation.

Under rain fed conditions the most common annual crop is wheat, though in modern agriculture this crop is more and more abandoned and shifted towards irrigated cropping. Hence, the key element in Mediterranean agriculture has become the availability of water. In other words, areas with little or no irrigation potential are abandoned for arable cropping and are left for grazing (cereals may then be grown as fodder), while all economic cropping is concentrated on irrigation schemes.

The variety of crops that can be grown under irrigation is vast and the choice is often determined by socio-economic and opportunity conditions rather than by soil or other physical parameters. Horticulture, citrus production and floriculture occupy the irrigated land nearby consumption centers or markets. The flower production area in Israel which supplies the European off-season market between November and January is located in the immediate neighborhood of Lod Airport (Tel Aviv) so as to allow an overnight delivery on the German or Scandinavian flower market. A similar situation exists for the fynbos flower production like Protea and Erica around Cape Town International Airport.

Large-scale commercial production of fodder crops, sunflower, sorghum, cotton, wheat, etc. is often situated at greater distance from the consumption centers. In recent years, there has been a growing competition for scarce water sources in some Mediterranean countries (e.g. Tunisia, Morocco, Spain) between irrigated agriculture, domestic water supply in urban areas, and the development of tourist complexes.

5.3. Extensive Grazing

Areas covered with poorer soils, either because of stoniness, rockiness or depth constraints, or because of their location in remote areas, are generally left to extensive grazing by sheep and goats. The problem with the latter group of animals is that they also eat young tree shoots and thus hamper natural regeneration of a tree vegetation. Traditional grazing practices include also a regular burning of the old grass cover and are often at the origin of devastating wildfires.

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Glossary

Decalcification : An internal soil that dissolves calcium carbonate and causes the replacement of calcium in the soil by H^+. This phenomenon occurs mostly as a consequence of the solubilizing action of water containing CO_2 and, therefore, requires a humid pedoclimate.

Epipedon : A surface soil horizon defined in Soil Taxonomy as a diagnostic feature for distinguishing differences in horizon development.

Characteristic types in Mediterranean soils are- anthropic epipedon- influenced by farming and characterized by high P_2O_5 contents; mollic epipedon- dark-colored organo-mineral surface layer with moderately high humus content and with high base saturation; ochric epipedon- light-colored organo-mineral low-humus-containing surface layer; and umbric epipedon- dark-colored organo-mineral surface layer with low base saturation.

Fragipan : A subsurface soil horizon, showing a degree of induration when dry but a weak to moderate degree of brittleness when moist.

Karst : A Serbo-Croatian term referring to the terrain created by limestone dissolution and characterized by a virtual absence of surface drainage, a series of surface hollows, depressions and fissures, collapse structures and an extensive subterranean drainage network.

Loess (or loss) : A homogeneous, fine grained silt-size wind-blown deposit covering extensive areas in Northern Europe and North America.

Pedoclimate : The temperature and moisture characteristics in the soil profile (mainly root zone).

Pedogenesis : The natural process of soil formation under the combined effect of climate, parent material, topography, time and biological activity.

Rejuvenation : The act of making younger. In soil science- to bring the unaltered material nearby the surface and re-starting soil formation after the surface layers are eroded.

Rubéfaction : A French term referring to the development of red matrix colors in Terra Rossa soils.

Solum : The entire A and B horizons of the same profile and, additionally, the layers with genetic features related to the development of these horizons, when located at the level of the C horizon (for example a duripan).

Solstice : The time during winter or summer when the overhead midday sun reaches its minimum or maximum declination from the equator. In the northern hemisphere the summer solstice is about 21 June, and the winter solstice is about 21 December.

Terra Rossa : Denomination of Red Mediterranean soils developed over (hard) limestone in older literature; later sometimes erroneously extended to all Mediterranean soils.

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